

How to Gauge Traces (Rev 7/01 [See note at end])

Douglas Brooks

Considerable information is available in various publications and handbooks about the electrical characteristics of wires by wire size (commonly called wire gauge.) But there is very little information readily available regarding how to apply that information to traces on printed circuit boards. There is, of course, the obvious manual relationship that can be created between the cross sectional area of a particular wire gauge and the cross sectional area of a trace. But there is almost no information available regarding how to go from a trace geometry to an equivalent wire gauge.

This column will show what relationships can be derived between trace area and wire gauge, and then how we can work with trace resistance as a function of size and temperature.

Background: The American Wire Gauge (AWG) system was originally designed by J. R. Brown in 1857 and was first known as the Brown & Sharp (B&S) Gauge. Wire was formed by drawing it through a series of decreasingly smaller diameter holes. The gauge roughly represented the number of steps involved in drawing the particular size. Thus, for example, a 24 gauge wire was drawn through 4 more steps than was a 20 gauge wire. **Figure 1** provides a current table of wire gauges and their associated wire diameters and cross-sectional areas.

In reviewing the literature, it is clear that there is no precise definition of what those stages are. But there is agreement on one thing: Gauge 0000 (4/0) is defined as having a diameter of .4600 inch and gauge 36 has a diameter of .0050 inch. The other gauges are more or less geometrically defined between these points. If that were exactly true, then the ratio of the diameter between any two adjacent gauges would be given by the equation (note that there are 39 gauge steps between gauge 0000 and gauge 36):

$$\frac{d_{\text{gauge}-1}}{d_{\text{gauge}}} = \sqrt[39]{\frac{0.4600}{0.0050}} = 1.1229322$$

If you apply this constant throughout the table, you get very close results between any two stages. But errors can accumulate and become very large across many stages. Therefore, the progression is approximately, but not exactly, geometric.

Equations: There is, however, a regular progression throughout the table. This can be seen in **Figure 2** where wire diameter and the Log_{10} of the wire diameter are graphed against wire gauge. The log of the wire diameter is an almost perfectly straight line. A curve fitted to this line has the following equation:

$$\text{Gauge} = -9.6954 - 19.8578 * \text{Log}_{10}(d)$$

where d = wire diameter in inches.

Figure 1
Table of wire gauge (AWG) and dimension for
solid copper wire.

Wire Gauge and Area Solid Copper Wire		
Gauge	d (in)	Area (Sq.In.)
0000	0.460000	0.1661901110
000	0.409600	0.1317678350
00	0.364800	0.1045199453
0	0.324900	0.0829065680
1	0.289300	0.0657334432
2	0.257600	0.0521172188
3	0.229400	0.0413310408
4	0.204300	0.0327813057
5	0.181900	0.0259869262
6	0.162000	0.0206119720
7	0.144300	0.0163539316
8	0.128500	0.0129686799
9	0.114400	0.0102787798
10	0.101900	0.0081552613
11	0.090740	0.0064667648
12	0.080810	0.0051288468
13	0.071960	0.0040669780
14	0.064080	0.0032250357
15	0.057070	0.0025580278
16	0.050820	0.0020284244
17	0.045260	0.0016088613
18	0.040300	0.0012755562
19	0.035890	0.0010116643
20	0.031960	0.0008022377
21	0.028460	0.0006361497
22	0.025350	0.0005047141
23	0.022570	0.0004000853
24	0.020100	0.0003173084
25	0.017900	0.0002516492
26	0.015940	0.0001995566
27	0.014200	0.0001583676
28	0.012640	0.0001254826
29	0.011260	0.0000995787
30	0.010030	0.0000790117
31	0.008928	0.0000626034
32	0.007950	0.0000496391
33	0.007080	0.0000393691
34	0.006305	0.0000312219
35	0.005615	0.0000247622
36	0.005000	0.0000196349
37	0.004453	0.0000155738
38	0.003965	0.0000123474
39	0.003531	0.0000097923
40	0.003145	0.0000077684
41	0.002800	0.0000061575
42	0.002490	0.0000048695
43	0.002220	0.0000038708
44	0.001970	0.0000030480
45	0.001760	0.0000024328
46	0.001570	0.0000019359

This article appeared in Printed Circuit Design, a CMP Media publication, January, 2001

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Traces on circuit boards, of course, are rectangular, not round. So the relationship to the diameter of the wire is not particularly meaningful. But if we can define an equation using diameter as a variable, we can also define an equation using cross-sectional area as a variable. When we do that we get the following result:

$$\text{Gauge} = -10.7 + 10 \cdot \log_{10}(1/a)$$

where a = cross-sectional area in square inches.

We can work both ways with this formula. If we know the cross-sectional area of our trace, we can calculate the equivalent wire gauge directly. If we want to solve for the trace area that will give us the equivalent of a particular wire gauge, then we solve:

$$\text{Area} = 10^{[-(\text{AWG} + 10.7)/10]}$$

Resistance: Tables of wire gauge often provide a resistance measure of some kind for each gauge. That way we can estimate the resistance of any length of wire we might be interested in. Calculating trace resistance is only slightly more complicated. Metals have a characteristic called "resistivity" (ρ) sometimes also called "specific resistance." Resistivity is defined by the relationship

$$R = \rho \cdot l / a$$

where R = resistance in Ohms, l = length and a = cross-sectional area. Units for resistivity are Ohm-unit where "unit" is the unit system for l and a . The resistivity for pure copper is often given as:

$$\rho = 1.724 \text{ microhm-cm, or}$$

$$\rho = .6788 \text{ microhm-in}$$

Therefore, the resistance of any copper trace can be found in a fairly straightforward manner by taking this value for resistivity, dividing it by the cross-sectional area of the trace, and then multiplying by the length of the trace. There is a minor complication

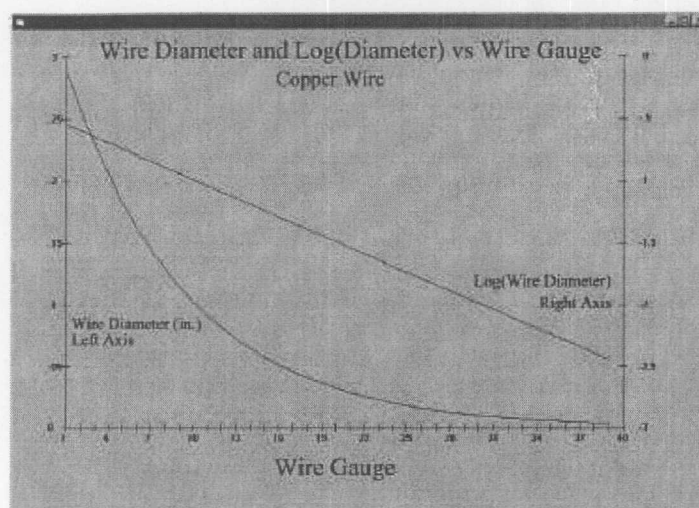


Figure 2
Relationship between wire diameter and AWG gauge.

here, however. Resistivity changes with temperature! Therefore, resistivity constants are usually given for a specific temperature, and that usually is 20°C. So this calculation will give the resistance of the trace at 20°C.

Temperature Effects: Resistance of a trace increases with temperature. A figure, called the "Temperature Coefficient of Resistance" is a measure of the magnitude of that change. The value we usually use for this measure is .00393. The way we use this constant to calculate the effect of temperature is as follows:

$$R2/R1 = 1 + .00393 \cdot (T2 - T1)$$

where $R1$ and $T1$ are the base resistance and temperature (in °C), respectively, $T2$ is the new temperature, and $R2$ is the resistance at this new temperature.

Calculator: All these calculations are straightforward, but tedious. UltraCAD has put together a free-ware calculator that does all these calculations for you. Figure 3 illustrates the calculator. It can be obtained from the UltraCAD website at www.ultracal.com. The calculator allows you to calculate any one of the equivalent wire gauge for a trace, its thickness, or its width, given the other two variables; the trace resistance given its length and temperature; and then the voltage drop along the trace given the current.

Solder Coat: One final point.... how much additional current carrying capacity does solder coat add to a trace? The answer may be surprising. The resistance of any conductor is a function of its resistivity. We can consider the trace and the solder coating to be parallel conductors. Assuming the solder coat has the same width and length as the trace, we need consider only the relative thickness of the trace and its coating.

Copper has a resistivity of 1.724 microhm-cm. Tin, on the other hand, has a resistivity of 11.5 microhm-cm, 6.7 times higher. Lead has a resistivity of

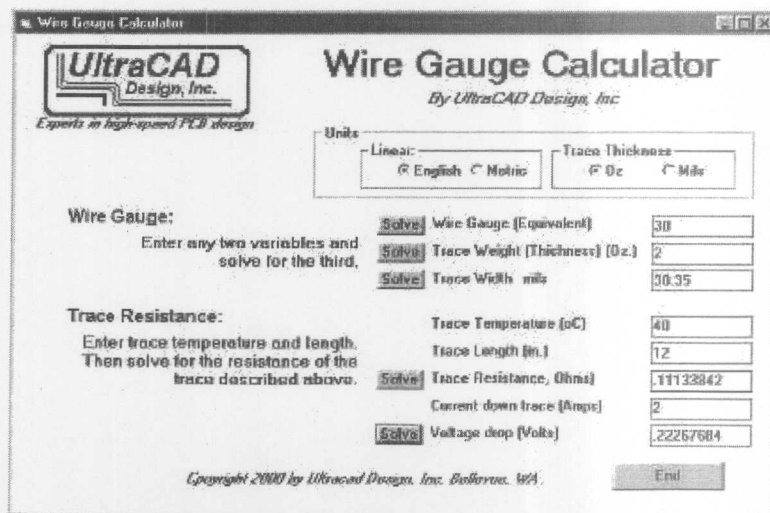


Figure 3

UltraCAD's freeware calculator will do gauge conversions and trace resistance calculations for you.

22 microhm-cm, almost 13 times higher. Therefore, depending on the tin/lead ratio, the resistivity of the solder coat will be something on the order of 10 times that of the copper trace for the same thickness. Since current divides between conductors inversely proportional to their resistance, equal thicknesses of copper trace and solder coat will result in approximately 90% of the current traveling through the copper trace (and only the balance through the solder.) In general, then, we can ignore the effects of solder coat as far as power carrying capacity and voltage drop is concerned, unless we need to know these values *very* precisely.³

My thanks to Brian Poindexter, Senior Design Engineer, Garmin Corporation, Olathe, KS. for pointing out in the original text an error in the formulas on page 2. The formulas should be, as now shown:

$$\text{Gauge} = -10.7 + 10 * \text{Log}_{10} (1/a)$$

$$\text{Area} = 10^{[-(\text{AWG} + 10.7)/10]}$$

Whatever error found its way into this paper did NOT find its way into the wire gauge calculator, which has always used these correct formulas.

Footnotes:

1. Buchsbaum's Complete Handbook of Practical Electronic Reference Data, 2nd Ed., Prentice Hall, 1978, p.22
2. Howard Johnson uses the equation $\text{AWG} = -10 - 20 * \text{Log}(d)$, which is a very close approximation and is certainly easier to use. See his High-Speed Digital Design, p412.
3. For a discussion of the current carrying capacity of traces themselves, see "Trace Currents and Temperatures", May, 1998, or "Temperature Rise in PCB Traces" at <http://www.ultracad.com>.